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LOCAL TURBULENT SKIN-FRICTION MEASUREMENTS ON A FLAT PLATE AT MACH NUMBERS FROM 2.5 TO 4.5 AND REYNOLDS NUMBERS UP TO 69 X 10^6

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SUMMARY

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A wind-tunnel investigation has been conducted to measure local turbulent skin friction on a 10-foot-long flat-plate model at local Mach numbers of 2.46, 2.91, 3.47, and 4.44 over a Reynolds number range between 5×10^6 and 69×10^6.

The skin-friction values measured in this investigation averaged between 0 and 5 percent above the predictions by the Sommer and Short T' method, but these differences may be within the accuracy of the measurements. Skin-friction balances with improved characteristics, together with surveys of the test flat-plate model, will be necessary in order to assess the reliability of the results.

Author

INTRODUCTION

The accurate knowledge of the level of skin friction is of great importance in the design of efficient supersonic aircraft, since skin-friction drag contributes such a large portion of the total drag of the vehicle at cruise conditions. The cruise condition will be at Reynolds numbers ranging to several hundred millions, significantly above 20×10^6 which is the upper limit for most supersonic skin-friction measurements, and the boundary layer will be predominantly turbulent. The data of references 1 to 4 are among those which go into the higher Reynolds number ranges. The differences among the various data amount to 15 percent between references 2 and 3, even though each of these two are internally consistent and repeatable to much smaller increments.

The correlation of experimental turbulent skin friction has generally tended to depend upon averaging data from a number of different sources. (See refs. 5 and 6, for example.) Therefore, more data in the higher Reynolds number range are required supersonically, and accuracy of measurements should be of prime importance. The present tests were conducted as a preliminary investigation to evaluate the instrumentation and test apparatus involved with floating-element skin-friction balances. Although the results are not as good as desired, they do add to the body of available skin-friction measurements.

The results were obtained from an experimental wind-tunnel investigation in which turbulent local skin friction was measured on a flat-plate model at Reynolds numbers between 5×10^6 and 69×10^6 and at free-stream Mach numbers of 2.50, 2.94, 3.50, and 4.53. Three skin-friction balances were located at different spanwise locations at a single longitudinal station near the trailing edge of the plate. Transition was tripped artificially near the model leading edge.

SYMBOLS

C_f local skin-friction coefficient, $\dfrac{F}{q_\delta S}$

F shear force measured by balance

M Mach number

p pressure

q dynamic pressure

R_x Reynolds number based on free-stream conditions and the plate length from leading edge to balance location

S wetted area of disk, 0.785 square inch

T temperature

x distance from leading edge to location of skin-friction balance

η_r temperature recovery factor, $\dfrac{T_{aw} - T_\infty}{T_o - T_\infty}$

Subscripts:

aw adiabatic wall

i incompressible

o free-stream stagnation

∞ free stream

δ conditions at edge of boundary layer

APPARATUS AND TESTS

Wind Tunnel

This investigation was conducted in the high-speed test section of the Langley Unitary Plan wind tunnel, which is a closed-throat, single-return tunnel with provisions for the control of the pressure, temperature, humidity, and Mach number of the enclosed air. The facility has two test sections (48 by 48 by 84 in.), and flow may be diverted from one to the other or can bypass both by means of an auxiliary piping arrangement. The test Mach numbers were obtained by means of an asymmetric sliding block-nozzle arrangement. The Reynolds number range was obtained by varying the stagnation pressure.

The nature of the asymmetric sliding-block nozzle gives rise to Mach number gradients within the test section. Unpublished calibration data indicate that there is a gradual variation of Mach number vertically of ± 1 percent at low values of Mach number to $\pm 1\frac{1}{2}$ percent at the high values. Longitudinally the Mach number varies in a wavy pattern by a maximum of $\pm 1/2$ percent, whereas laterally there is essentially no change. A variation in M of up to 1 percent occurs over the stagnation-pressure range, but this is accounted for by the tunnel calibration curves. Limited flow angle survey results are available for test-section stations between 20 inches and 50 inches which indicate average up-flow angles of 0.2° at $M = 2.5$ increasing to 0.9° at $M = 4.5$.

Model

The flat-plate model (fig. 1) was 125.3 inches long by 48 inches wide and extended from approximately 21 inches ahead of the 84-inch nominal test section to 20 inches downstream. The plate spanned the test section of the tunnel with the flat surface down and at the center line. The plate was sealed at the sides to prevent flow leakage from one surface to the other. Additional model information may be found in reference 7. At the rearmost section of the plate was a housing with provisions for mounting skin-friction balances at three spanwise positions at a distance of 122 inches from the leading edge of the plate. The leading-edge thickness of the plate was about 0.060 inch and the surface finish of the plate was approximately 10 to 15 microinches.

Instrumentation

A sketch of one of the floating-element skin-friction balances used in this investigation is shown in figure 2. The balances, which were designed and built by the Defense Research Laboratory, University of Texas, were loaned to the Langley Research Center. The description of the balances and their operation is found in reference 8. A four-channel carrier amplifier was used in conjunction with a millivolt potentiometer to obtain and read out balance output data which were recorded on punch cards. The three balances used in this investigation had full-scale ranges of approximately 0.0087, 0.0089, and 0.0200 pound and were designated balances 1, 2, and 3, respectively. Each was operated with a small preload which was accounted for in the calibrations. The preload was due to adjustment of the balances so as to have the floating element sprung up against the upstream edge of the case when there was no shear load on the element.

All three balances were calibrated in place in the model both before and after the tests and the results indicated a scatter of approximately ±2 percent of full-scale load about a linear calibration. The scatter was independent of load level.

The balances were sensitive to change in ambient temperature. For the most part, the zero drift variations were repeatable, with a typical maximum drift being about 4 percent of full-scale load for the highest test temperature. This effect was minimized by utilizing "hot zeroes" (see section "Tests") which repeated to within a maximum of 1 percent. The results of bench calibrations performed on several similar balances indicated no change in sensitivity between temperatures of 75° F and 95° F.

The floating element of each balance was alined with its case so as to be several ten-thousandths of an inch below the case. This procedure was used in order to assure no protrusion of the element above its case, as protrusion produces a greater increment in indicated drag than does a corresponding opposite alinement. (See ref. 9.) The balance case was alined in the same manner with respect to the plate surface.

Tests

The test conditions are summarized in the following table:

M_∞	T_o, °F	Computed* T_{aw}, °F	p_o, psia	R_x
2.50	150	113	5 to 30	8.6×10^6 to 51.8×10^6
2.94	150	108	5 to 50	6.8 to 68.7
3.50	150	102	5 to 55	5.1 to 56.1
4.53	175	119	15 to 85	8.8 to 49.8

*Recovery factor assumed to be 0.89.

The tests were conducted by operating the tunnel at the desired test Mach number and stagnation temperature for a short time in order to permit the apparatus to reach equilibrium temperature, which is essentially adiabatic-wall temperature, before taking data. Data were recorded at each of a number of values of stagnation pressure after the pressure had stabilized. Data were taken at intervals both ascending and descending in pressure.

Hot zeroes were taken at each Mach number by diverting the flow past the test section while at a low stagnation pressure to provide the desired no-flow conditions with instrumentation at normal operating temperature. The hot zeroes were, in some cases, taken before recording data, but always after taking data at each Mach number.

All runs were made consecutively, as the Mach number was changed remotely between each run while the tunnel was operating at low stagnation pressures. The first and last runs were made at the same Mach number ($M = 2.94$) to serve as check points.

The model was installed at a geometric angle of attack of zero and transition was fixed near the leading edge of the plate with a band of No. 60 carborundum grit.

No measurements of plate Mach numbers were made during the present tests. Velocity profiles measured in reference 8 on this model were not measured with sufficient accuracy for the present purposes. However, a boundary-layer rake was calibrated, subsequent to the present tests, on this flat plate at several conditions ($x = 116$ inches at $M_\infty = 2.49$ and 2.98 and $x = 41$ inches at $M_\infty = 4.06$ and 4.65). The unpublished results indicate that the local Mach number at the edge of the boundary layer M_δ was less than these values of M_∞ by 0.04, 0.025, 0.050, and 0.100, respectively. These values are in fair agreement with estimates ($M_\delta - M_\infty = -0.01, -0.01, -0.045$, and -0.09) made by assuming the flat plate to be at a negative angle of attack equal to the average test-section flow angle.

Values of M_δ for the present test conditions have been obtained from the unpublished probe results and are used in the computation of the skin-friction data. The Mach number correction was obtained from a plot of measured $M_\delta - M_\infty$ against M_∞ and faired to yield the values given in the following table with corresponding values of $\Delta q/q$ also shown to indicate the effect of the change in M on skin-friction coefficient:

M_∞	$M_\delta - M_\infty$	$\Delta q/q$, percent
2.50	-0.040	2.9
2.94	-.025	2.1
3.50	-.025	2.2
4.53	-.087	6.8

The values of M_δ used in data reduction are to be considered as estimates, used only in the absence of more applicable measurements.

RESULTS AND DISCUSSION

The local turbulent skin-friction coefficients, plotted as a function of Reynolds number, are shown in figures 3 to 6 for the four test Mach numbers.

The results are also given in table I. Each symbol represents the results of a different balance. As a comparison, the solid line represents the local turbulent skin-friction coefficients which are predicted by the Sommer and Short T' method (ref. 10).

At every Mach number the repeat points made during each run were in agreement from about ±1 percent at the high loads to ±2 percent at the low loads. The check run at $M = 2.91$ (not plotted) repeated within the same limits. The results of balance 3 should be discounted at $M = 4.44$ since the balance was measuring loads that ranged from only 3 to 13 percent of its full-load capacity.

The several balances are seen to yield results that differ from the average by from ±2 percent to ±5 percent depending upon the Mach number. The average level of the local skin friction appears to be higher than that calculated by the Sommer and Short T' method by a value between 0 to 5 percent at each Mach number.

Figure 7 is a summary plot showing the ratio of compressible to incompressible skin friction plotted as a function of Mach number at a constant Reynolds number of 50×10^6. Again, the solid line represents the values predicted by the Sommer and Short T' method. Only flat-plate results by other investigators are shown for comparison with the data of the present tests. The present data are seen to range from 3 percent below to 8 percent above the predictions of the reference theory, and fall close to the level of the results of reference 2 and below the results of reference 3.

The differences in the results as measured by the three balances might be attributed to either of two sources: spanwise variation in boundary-layer characteristics across the test plate or differences in characteristics of the installed balances. Note that, in reference 2, it was found that these same balances, when interchanged at a given location, did not provide identical results. It is possible that the present data are within the installed accuracy of the instrumentation. In any event, if proper assessment of the reliability of the results is to be achieved, improved balance characteristics as well as surveys of the plate pressures and boundary-layer profiles will be necessary.

CONCLUDING REMARKS

A wind-tunnel investigation has been conducted to measure local turbulent skin friction on a 10-foot-long flat-plate model at local Mach numbers of 2.46, 2.91, 3.47, and 4.44 over a Reynolds number range between 5×10^6 and 69×10^6.

The skin-friction values measured in this investigation averaged between 0 and 5 percent above the predictions by the Sommer and Short T' method, but these differences may be within the accuracy of the measurements. Skin-friction balances with improved characteristics, together with flow surveys of the test flat-plate model will be necessary in order to assess the reliability of the results.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., April 28, 1965.

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TABLE I.- EXPERIMENTAL DATA

M_δ	p_o, lb/sq ft abs	T_o, °F	F, lb, for - Balance 1	Balance 2	Balance 3	q_δ, lb/sq ft abs	R_x	C_f for - Balance 1	Balance 2	Balance 3
2.915	718	150	----------	1.20×10^{-3}	1.10×10^{-3}	132.2	6.8×10^{6}	----------	1.66×10^{-3}	1.53×10^{-3}
2.915	1 439	150	2.14×10^{-3}	2.12	2.01	265.0	13.6	1.48×10^{-3}	1.46	1.39
2.915	2 162	150	3.05	2.96	2.89	398.0	20.4	1.40	1.36	1.33
2.915	2 880	150	3.86	3.80	3.71	530.2	27.3	1.33	1.31	1.28
2.915	3 599	150	4.60	4.55	4.48	662.5	34.1	1.27	1.26	1.24
2.915	2 877	150	3.81	3.85	3.72	529.6	27.2	1.32	1.33	1.29
2.915	3 602	150	4.50	4.67	4.49	663.1	34.1	1.24	1.29	1.24
2.915	4 319	150	5.22	5.39	5.16	795.5	40.9	1.20	1.24	1.19
2.915	5 039	150	6.13	6.02	5.92	928.2	47.8	1.21	1.19	1.17
2.915	5 798	150	6.93	6.71	6.68	1 067.9	54.9	1.19	1.15	1.14
2.915	6 519	150	7.73	7.48	7.42	1 200.2	61.8	1.18	1.14	1.13
2.915	6 888	150	8.15	7.89	7.83	1 268.1	65.3	1.18	1.14	1.13
2.915	7 248	150	8.51	8.20	8.18	1 334.9	68.7	1.17	1.12	1.12
2.915	6 875	150	8.16	7.83	7.82	1 265.7	65.1	1.18	1.13	1.13
2.915	6 160	150	7.42	7.12	7.08	1 134.0	58.4	1.20	1.15	1.14
2.915	5 445	150	6.61	6.37	6.33	1 002.4	51.6	1.21	1.16	1.15
2.915	4 674	150	5.79	5.71	5.57	860.9	44.3	1.23	1.21	1.18
2.915	3 961	150	4.95	5.00	4.81	729.2	37.5	1.24	1.25	1.21
2.915	2 517	150	3.44	3.44	3.35	463.5	23.8	1.36	1.36	1.32
2.915	1 083	150	1.71	1.72	1.64	199.6	10.2	1.57	1.58	1.50
2.460	720	150	1.84	1.79	1.72	190.1	8.6	1.78	1.73	1.66
2.460	1 437	150	3.35	3.24	3.18	378.9	17.2	1.62	1.57	1.54
2.460	2 159	150	4.71	4.57	4.57	569.5	25.9	1.57	1.47	1.47
2.460	2 880	150	6.18	5.85	5.88	759.6	34.5	1.49	1.41	1.42
2.460	3 597	150	7.69	7.07	7.12	948.8	43.1	1.48	1.36	1.37
2.460	4 318	150	8.93	8.30	8.38	1 139.0	51.8	1.43	1.33	1.35
2.460	3 956	150	8.36	7.71	7.70	1 043.5	47.4	1.47	1.35	1.35
2.460	3 242	150	6.94	6.55	6.54	855.1	38.9	1.48	1.40	1.40
2.460	2 521	150	5.55	5.30	5.23	665.0	30.2	1.53	1.46	1.44
2.460	1 797	150	4.08	3.98	3.90	473.9	21.5	1.57	1.54	1.51
2.460	1 078	150	2.68	2.58	2.51	284.3	12.9	1.73	1.66	1.62
4.423	2 154	175	----------	.67	----------	113.0	8.8	----------	1.09	----------
4.433	3 601	175	----------	1.00	.74	185.6	14.5	----------	.99	.73
4.433	5 040	175	----------	1.34	1.08	260.8	20.4	----------	.94	.76
4.443	6 527	175	1.64	1.66	1.41	334.4	26.4	.90	.91	.77
4.443	7 966	175	1.94	1.99	1.73	408.4	32.2	.87	.89	.78
4.443	9 414	175	2.26	2.31	2.03	482.4	38.0	.86	.88	.77
4.443	10 852	175	2.59	2.63	2.35	556.3	43.9	.85	.87	.77
4.443	12 286	175	2.91	2.96	2.66	630.3	49.7	.84	.86	.77
4.443	11 553	175	2.76	2.83	2.51	593.3	46.8	.85	.87	.77
4.443	10 129	175	2.46	2.55	2.07	519.4	41.0	.87	.90	.73
4.443	8 695	175	2.15	2.27	1.69	445.4	35.2	.89	.99	.70
4.443	7 252	175	1.84	1.96	1.41	371.4	29.3	.91	.97	.69
4.443	5 798	175	1.51	1.66	1.14	297.5	23.5	.93	1.02	.70
4.433	4 318	175	----------	1.33	.84	224.0	17.5	----------	1.09	.69
4.423	2 888	175	----------	1.00	.53	151.2	11.8	----------	1.22	.65
4.433	3 602	175	----------	1.16	.71	185.7	14.5	----------	1.15	.70
4.423	2 878	175	----------	.95	.58	149.7	11.7	----------	1.16	.71
4.443	5 797	175	1.54	1.59	1.28	297.5	23.5	.95	.98	.79
4.443	8 681	175	2.14	2.21	1.91	445.4	35.2	.88	.91	.79
4.443	11 535	175	2.76	2.83	2.53	591.8	46.7	.86	.88	.78
3.435	718	150	----------	.96	.73	85.7	5.2	----------	2.06	1.56
3.455	1 439	150	----------	1.46	1.20	168.2	10.3	----------	1.59	1.30
3.475	2 881	150	2.30	2.38	2.10	331.4	20.3	1.27	1.31	1.16
3.475	4 315	150	3.27	3.28	3.01	496.3	30.5	1.21	1.22	1.11
3.475	5 796	150	4.20	4.12	3.87	666.4	40.9	1.16	1.14	1.06
3.475	7 241	150	5.08	4.95	4.73	832.1	51.1	1.12	1.09	1.04
3.475	7 966	150	5.52	5.35	5.16	915.4	56.2	1.11	1.07	1.03
3.475	6 523	150	4.65	4.51	4.32	749.7	46.0	1.14	1.10	1.06
3.475	5 083	150	3.76	3.63	3.46	583.9	35.8	1.18	1.14	1.09
3.475	3 601	150	2.80	2.69	2.59	413.8	25.4	1.24	1.19	1.15
3.475	2 160	150	1.83	1.74	1.67	248.1	15.2	1.36	1.29	1.24
2.915	718	150	----------	1.23	1.14	132.3	6.8	----------	1.71	1.58
2.915	1 444	150	2.16	2.16	2.07	265.8	13.7	1.49	1.49	1.43
2.915	2 158	150	3.05	3.06	2.95	397.4	20.5	1.41	1.41	1.36
2.915	2 882	150	3.80	3.67	3.78	530.9	27.4	1.31	1.34	1.31
2.915	3 610	150	4.53	4.68	4.52	665.0	34.2	1.25	1.29	1.25
2.915	4 326	150	5.37	5.35	5.22	796.6	41.0	1.24	1.23	1.20
2.915	5 037	150	6.19	6.02	5.94	927.7	47.8	1.22	1.19	1.18
2.915	5 802	150	7.02	6.74	6.72	1 068.6	55.0	1.21	1.16	1.15
2.915	6 523	150	7.78	7.47	7.49	1 201.4	61.9	1.19	1.14	1.14
2.915	4 677	150	5.83	5.71	5.59	861.5	44.4	1.24	1.22	1.19
2.915	3 241	150	4.23	4.27	4.15	597.0	30.8	1.30	1.31	1.28
2.915	1 797	150	2.69	2.60	2.53	331.3	17.1	1.49	1.44	1.40

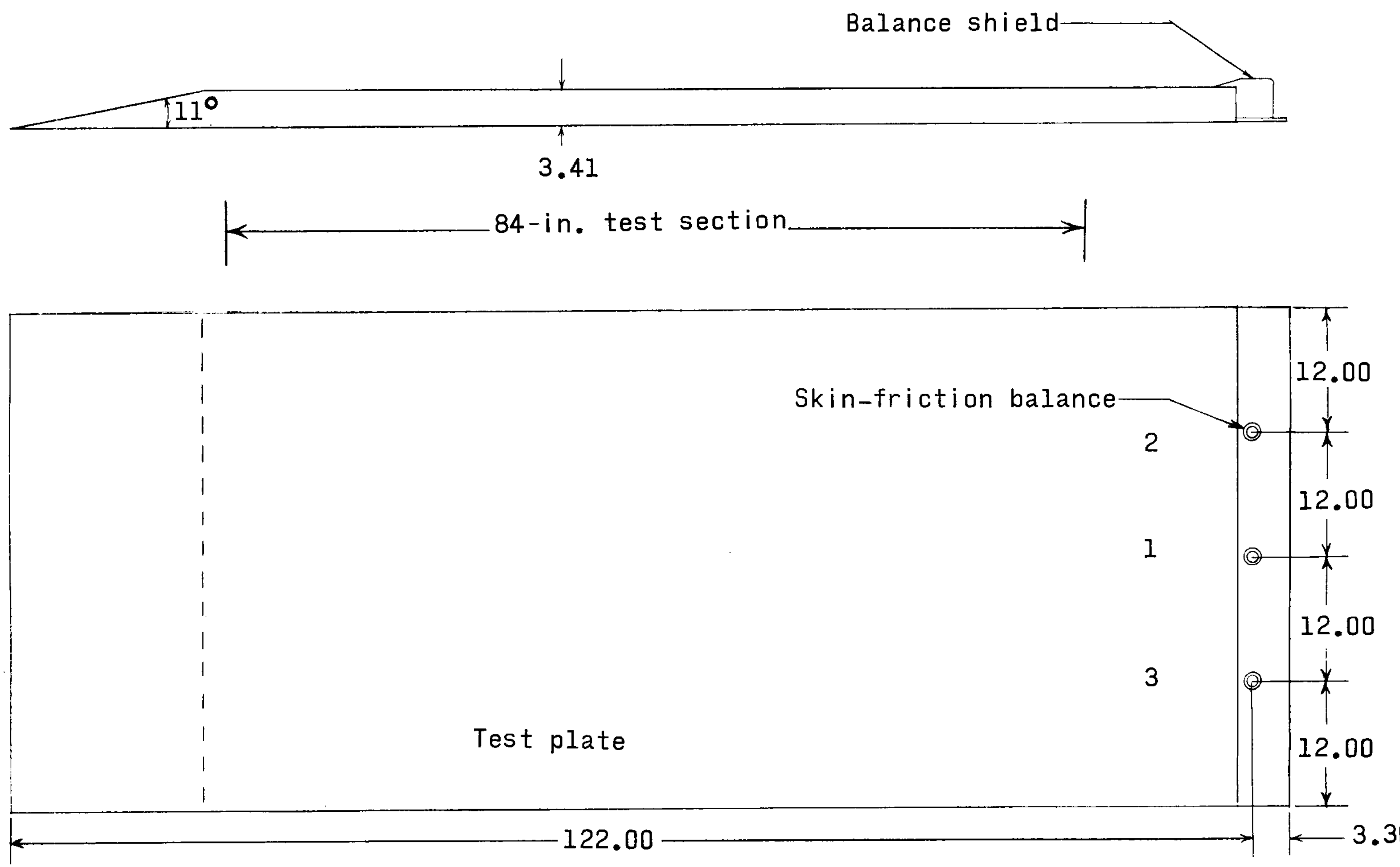

Figure 1. - Sketch of flat-plate model. All dimensions are in inches unless otherwise noted.

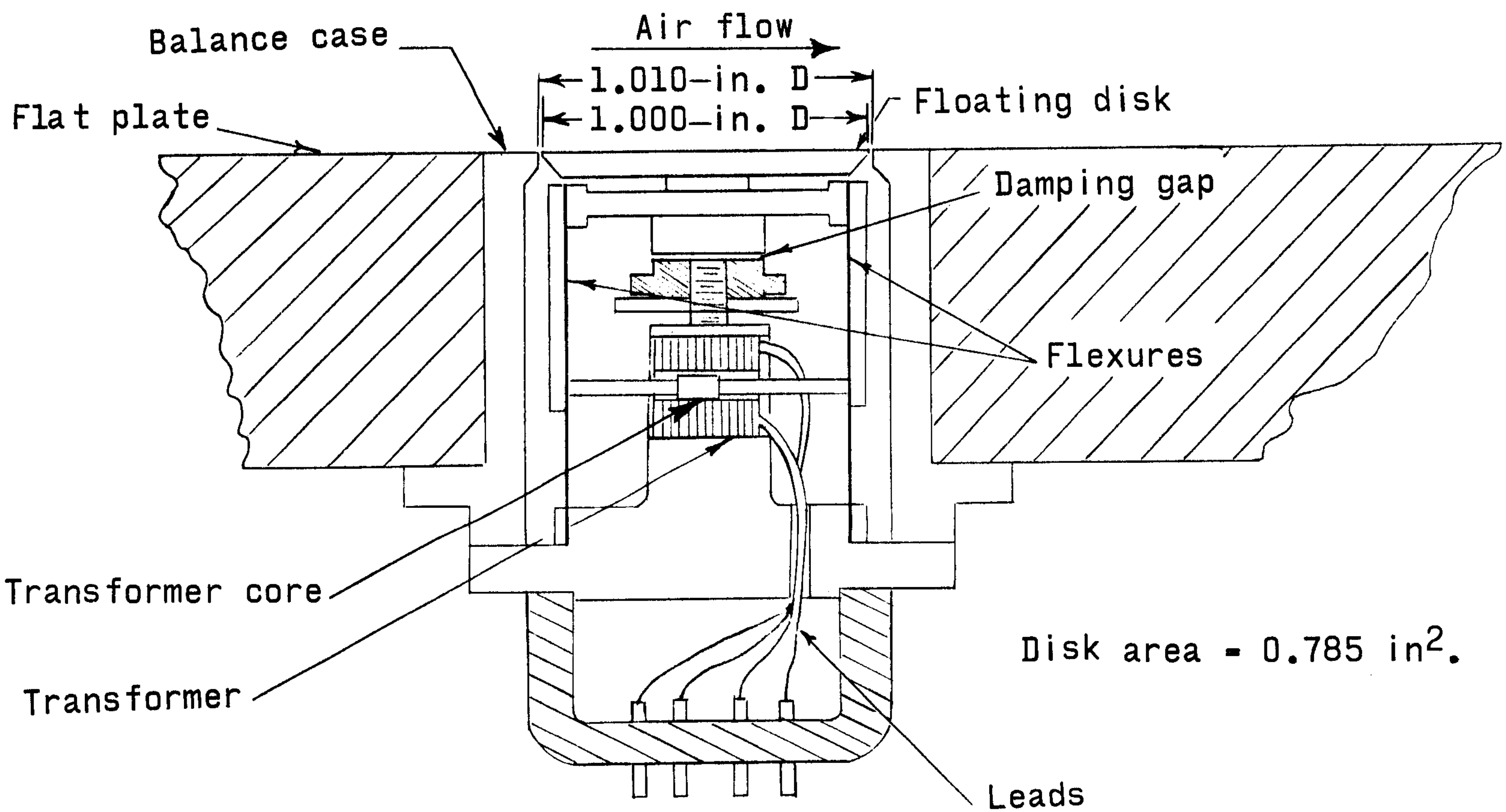

Figure 2. - Schematic drawing of a typical floating-element balance.

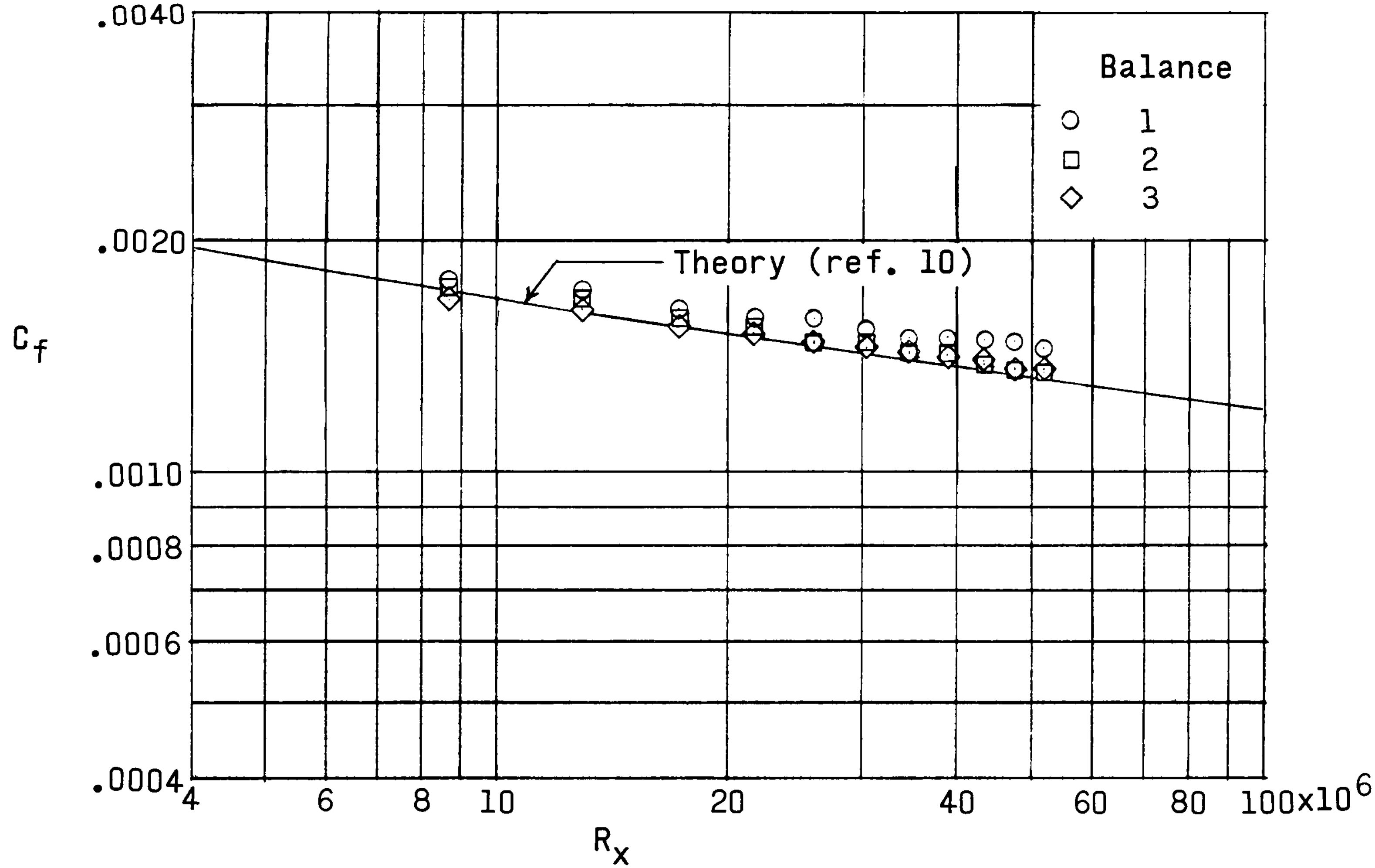

Figure 3. - Variation of local skin-friction coefficient with Reynolds number for M_δ = 2.46.

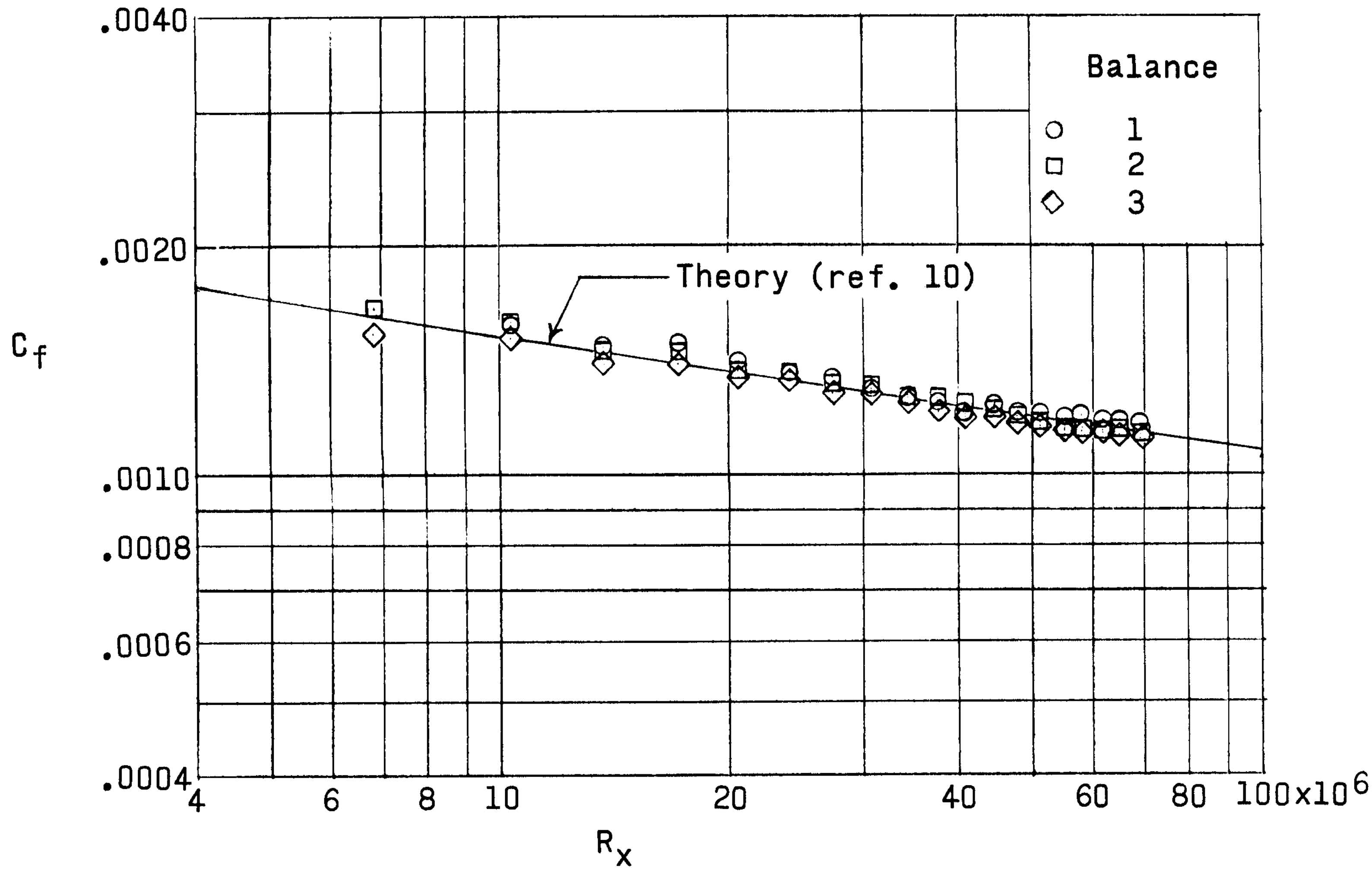

Figure 4. - Variation of local skin-friction coefficient with Reynolds number for $M_\delta = 2.91$.

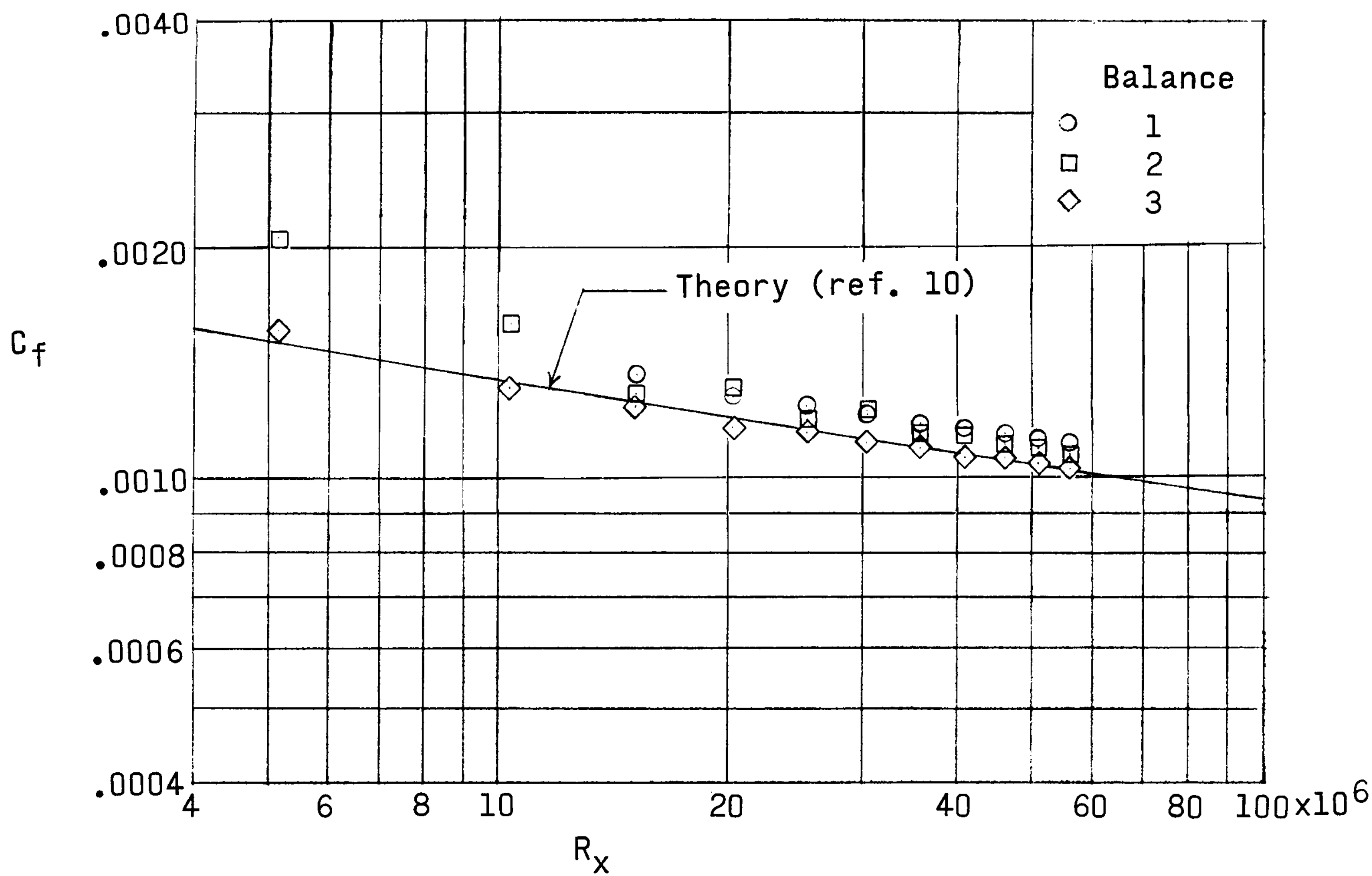

Figure 5. - Variation of local skin-friction coefficient with Reynolds number for $M_\delta = 3.47$.

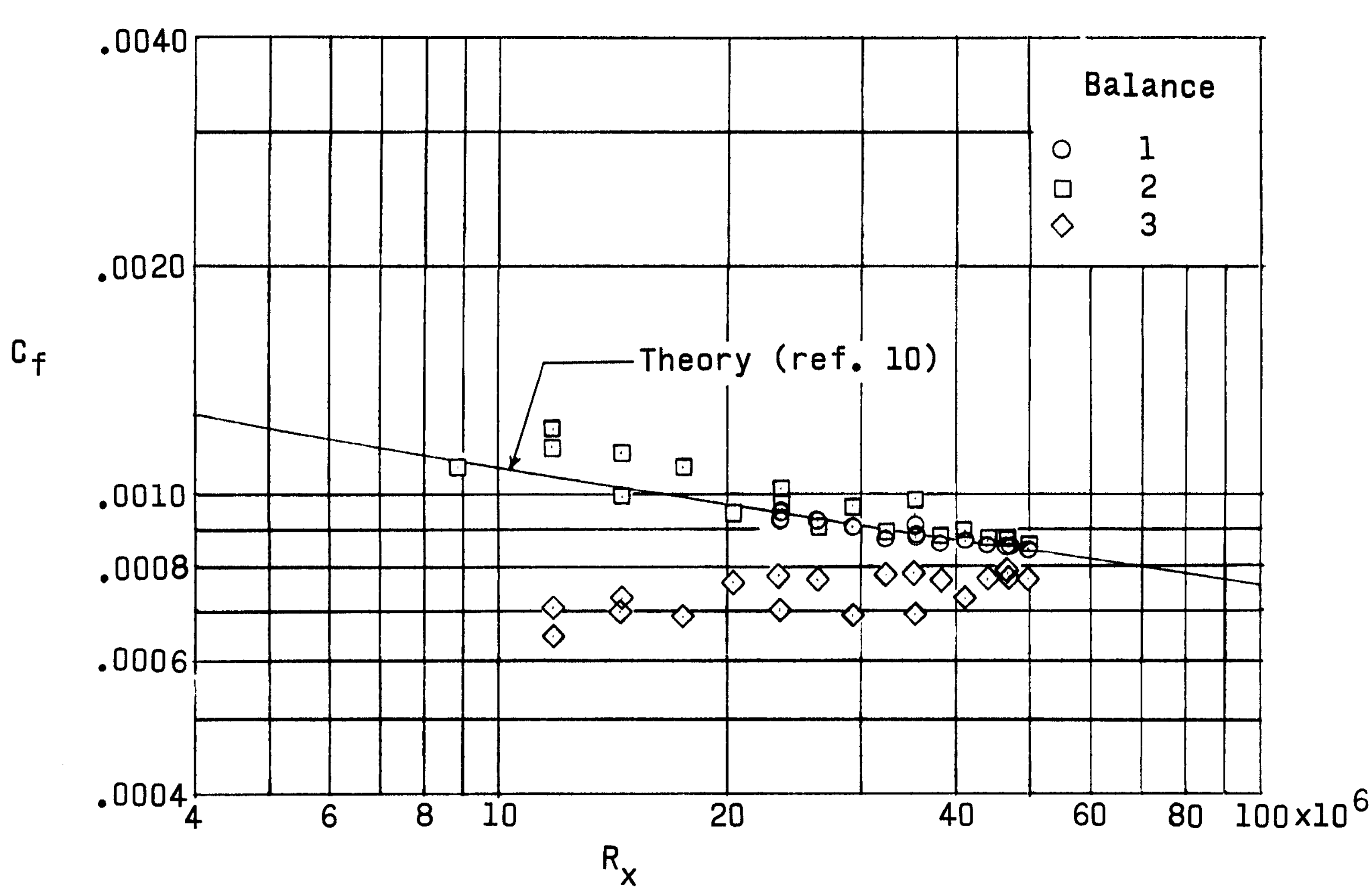

Figure 6. - Variation of local skin-friction coefficient with Reynolds number for $M_\delta = 4.44$.

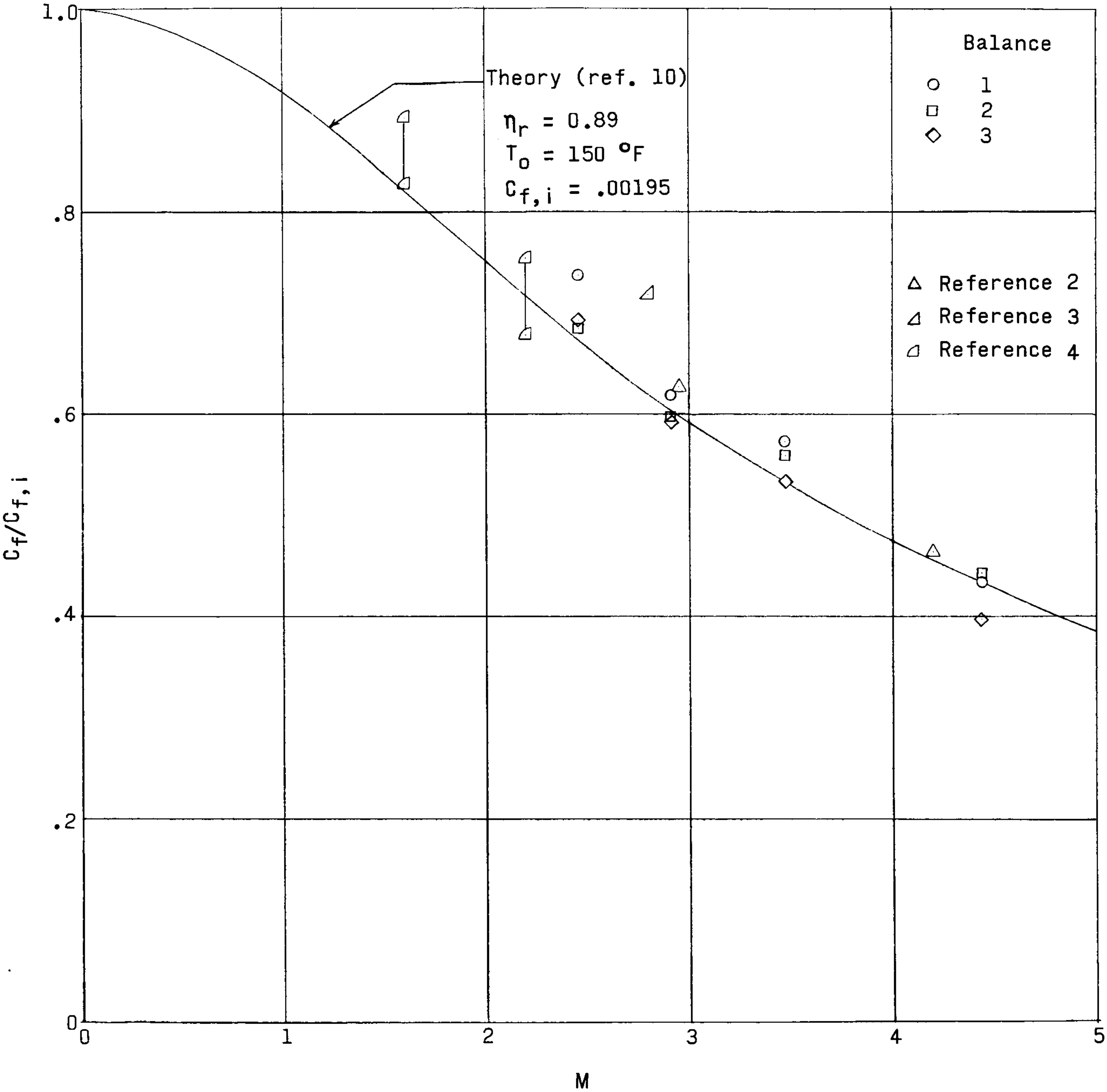

Figure 7. - Variation of ratio of compressibile to incompressible local skin-friction coefficient with Mach number. $R_X = 50 \times 10^6$.

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